Signature of saturation in p+A run at the LHC

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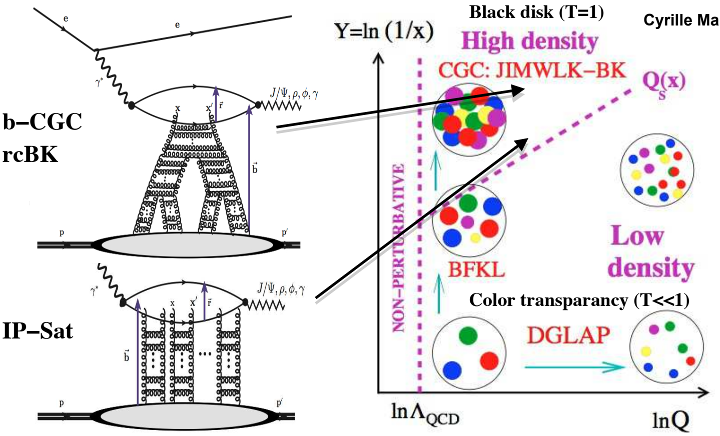
Road map of strong interaction

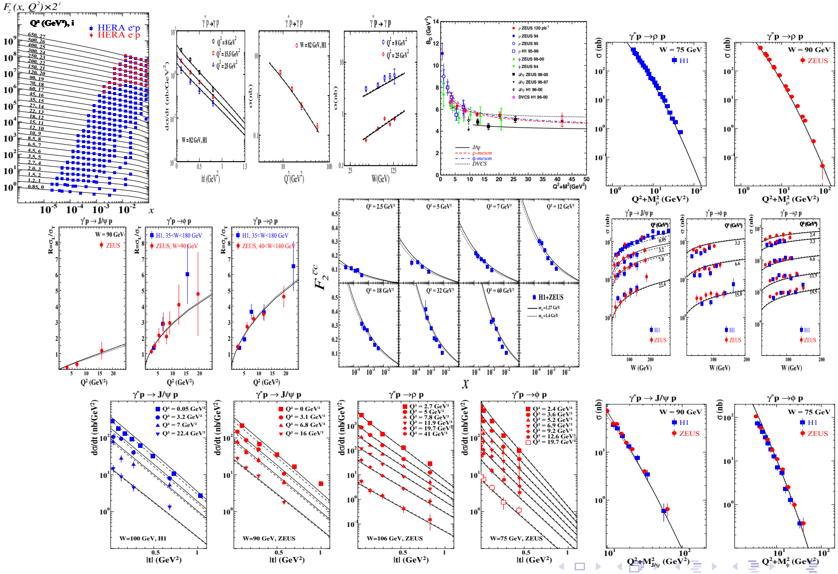
For introduction see:
Cyrille Marquet`s talk



- Dilute regime: Bjorken limit in QCD $s \to \infty;\, Q^2 \to \infty;\, x \approx \frac{Q^2}{s} = \text{fixed}$
  Asymptotic freedom, Machinery of precision pQCD...
- Dense regime: Regge limit in QCD $s \to \infty;\, x \to 0;\, Q^2 = \text{fixed}$
  Physics of strong fields in QCD, Saturation, Multi-particle production...

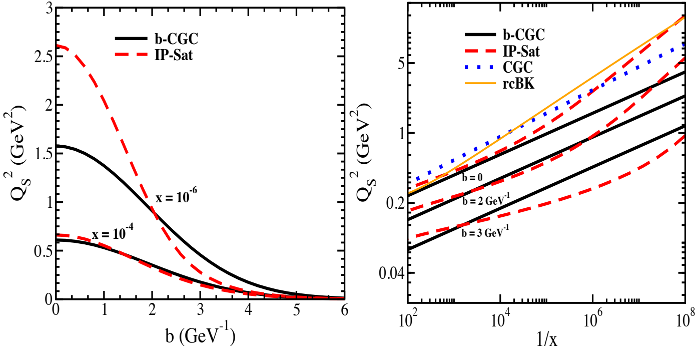
A unified description of e+p ($x < 0.01$) inclusive & exclusive data in the CGC

Rezaeian, Siddikov, Van de Klundert, Venugopalan (2013); Rezaeian, Schmidt (2013)



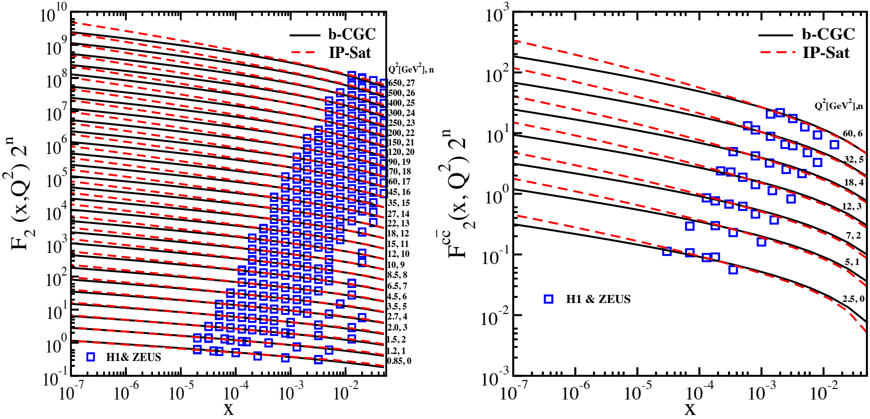
Saturation scale of Proton extracted from HERA data: IP-Sat v. b-CGC v. rcBK

Rezaeian and Schmidt, arXiv:1307.0825



- IP-Sat and b-CGC are impact-parameter dependent while rcBK is not.
- Order of magnitude discrepancies in saturation scale extracted from different models→ sizable uncertainties in predictions of various observables.
- Current small-x data do not put enough constrains on saturation models.

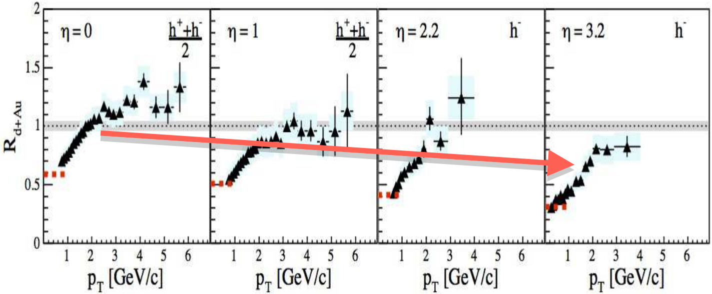
Saturation scale of Proton extracted from HERA data: IP-Sat v. b-CGC v. rcBK



- The difference among models can be considered as our current theoretical uncertainties → sizable effect at small-x.

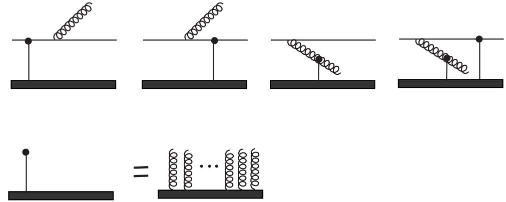
Signatures of the CGC in d+A@RHIC: Initial-state effect

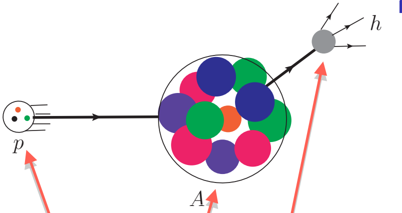
$$R_{pA}(\eta, p_\perp) \equiv \frac{1}{N_{coll}} \frac{\left.\frac{dN_h}{d^2p_\perp d\eta}\right|_{pA}}{\left.\frac{dN_h}{d^2p_\perp d\eta}\right|_{pp}} \simeq \frac{1}{A^{1/3}} \frac{\Phi_A(Y, p_\perp)}{\Phi_p(Y, p_\perp)}\,.$$



- Kinematic limit for particle production at RHIC and the LHC (at fixed η) are very different.

Inclusive hadron production in pA collisions; revisited





Dumitru, Hayashigaki, Jalilian-Marian,hep-ph/0506308; Altinoluk, Kovner, arXiv:1102.5327; Chirilli, Xiao, Yuan,arXiv:1112.1061

$$\frac{dN^{pA\to hX}}{d^2p_T\,d\eta} = \frac{K}{(2\pi)^2}\left[\int_{x_F}^{1}\frac{dz}{z^2}\left[x_1 f_g(x_1,Q^2)N_A(x_2,\frac{p_T}{z})D_{h/g}(z,Q)+\Sigma_q x_1 f_q(x_1,Q^2)N_F(x_2,\frac{p_T}{z})D_{h/q}(z,Q)\right]\right.$$

$$\left. + \int_{x_F}^{1}\frac{dz}{z^2}\frac{\alpha_s^{in}}{2\pi^2}\frac{z^4}{p_T^4}\int_{k_T^2<Q^2} d^2k_T\,k_T^2 N_F(k_T,x_2)\int_{x_1}^{1}\frac{d\xi}{\xi}\Sigma_{i,j=q,\bar{q},g}\,w_{i/j}(\xi)P_{i/j}(\xi)x_1 f_j(\frac{x_1}{\xi},Q)D_{h/i}(z,Q)\right]$$

$$\frac{\partial\mathcal{N}_{A(F)}(r,x)}{\partial\ln(x_0/x)} = \int d^2\vec{r}_1\;K^{\mathrm{run}}(\vec{r},\vec{r}_1,\vec{r}_2)\left[\mathcal{N}_{A(F)}(r_1,x)+\mathcal{N}_{A(F)}(r_2,x)-\mathcal{N}_{A(F)}(r,x)-\mathcal{N}_{A(F)}(r_1,x)\,\mathcal{N}_{A(F)}(r_2,x)\right]$$

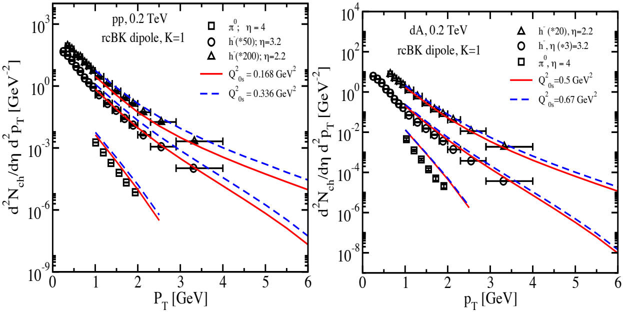
BK-JIMWLK eq

Initial condition: $\mathcal{N}(r,Y=0) = 1-\exp\left[-\frac{\left(r^2\,Q_{0s}^2\right)^{\gamma}}{4}\ln\left(\frac{1}{\Lambda\,r}+e\right)\right]$

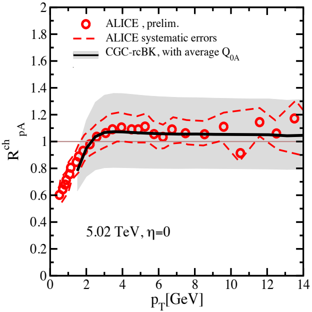
For solutions of $\mathcal{N}$: **Albacete and Dumitru, arXiv:1011.5161**

Inclusive hadron production in d+Au@RHIC and p+Pb@LHC

Jalilian-Marian, Rezaeian, arXiv:1110.2810



Rezaeian, arXiv:1210.2385

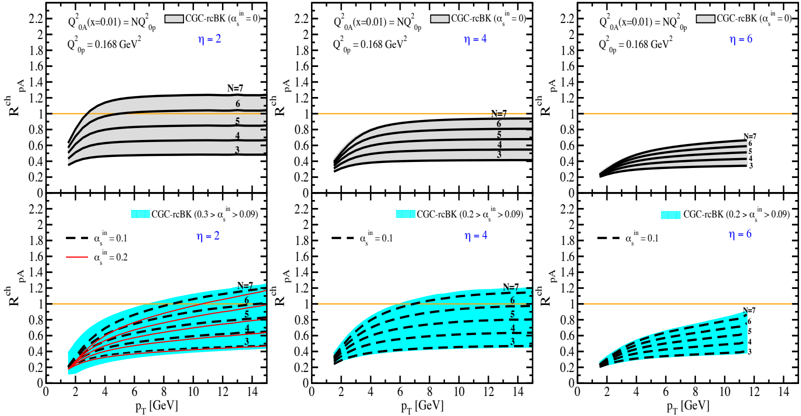


- What is the role of energy loss effect in the above (not included)?.

See Francois Arleo, Carlos Salgado and Maria Zurita`s talks

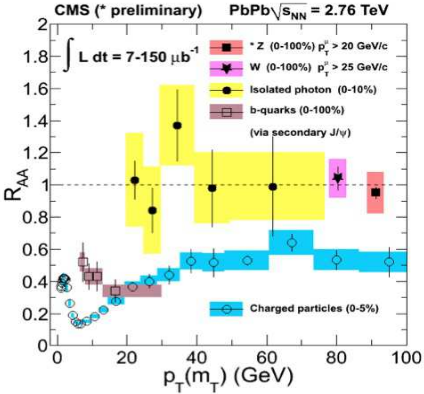
CGC predictions for R^h_{pA} at 5 TeV

Rezaeian, arXiv:1210.2385



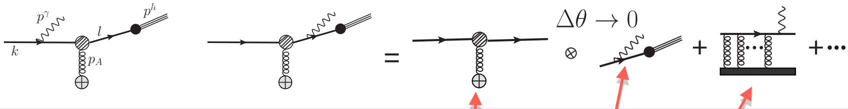
- One can readily extract N or Q_{0A} from data at a given η → **uncertainties band will be then significantly reduced at other η and for all other observables.**

Inclusive prompt photon production



- In AA collisions all hadrons are strongly quenched except prompt photon → **prompt photon is a good probe of initial-state (Saturation) effect.**
- Prompt photon is free from hadronization mess.
- Semi-inclusive photon-hadron production (only dipole appears) **is better under control in the CGC approach** compared to dihadron production.

Inclusive prompt photon production in high-energy pA collisions



Gelis, Jalilian-Marian, hep-ph/0205037; Jalilian-Marian, Rezaeian, arXiv:1204.1319

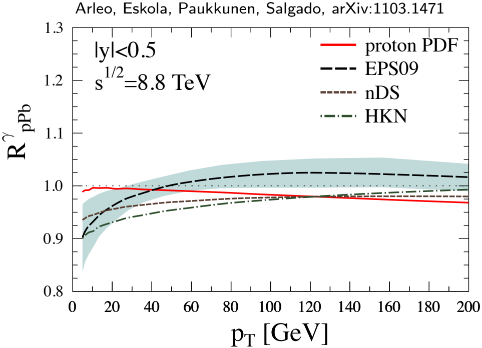
$$\frac{d\sigma^{p\,A\to\gamma(p^\gamma)\,X}}{d^2\vec{b_T}\,d^2\vec{p_T}^{\,\gamma}\,d\eta_\gamma} = \frac{K}{(2\pi)^2}\Big[\int_{x_q^{min}}^{1} dx_q\, f_q(x_q,\,Q^2)\,\frac{1}{z}\,N_F(x_g,\,p_T^\gamma/z)D_{\gamma/q}(z,\,Q^2)$$

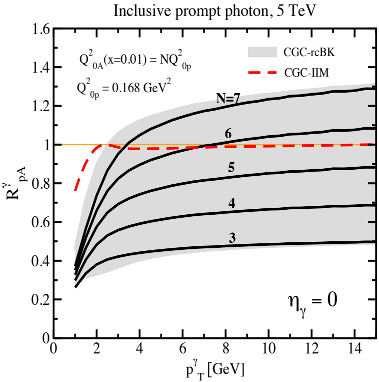
$$+\ \frac{e_q^2\,\alpha_{em}}{2\pi^2(p_T^\gamma)^4}\int_{x_q^{min}}^{1} dx_q\, f_q(x_q,\,Q^2)z^2[1+(1-z)^2]\int_{l_T^2<Q^2} d^2\vec{l_T}\; l_T^2\; N_F(\bar{x}_g,\,l_T)\Big],$$

$$x_g = x_q\,e^{-2\,\eta_\gamma}, \qquad \bar{x}_g = \frac{1}{x_q\,S}\left[\frac{(p_T^\gamma)^2}{z}+\frac{(l_T-p_T^\gamma)^2}{1-z}\right] \qquad z = \frac{p_T^\gamma}{x_q\,\sqrt{S}}\,e^{\eta_\gamma}, \qquad \text{with} \qquad x_q^{min} = \frac{p_T^\gamma}{\sqrt{S}}\,e^{\eta_\gamma}.$$

- Both fragmentation and direct photon are sensitive to saturation via N_F. However, direct photon is more sensitive to the saturation effects.
- pA is different from dA (unlike hadron production) due to charge squared of quarks → non-trivial isospin effect.

Inclusive photon production in p+A@LHC: collinear v. CGC

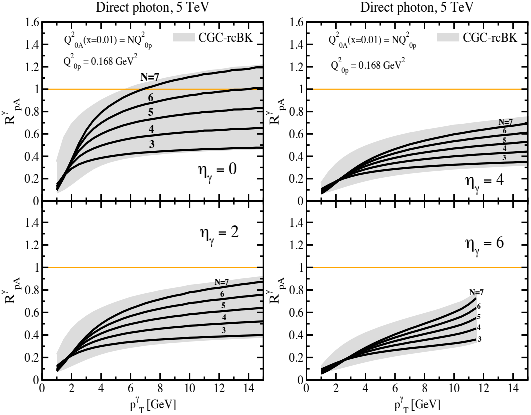


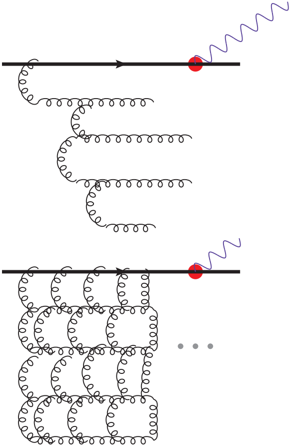


- To clearly discriminate between two approaches, forward rapidities measurements of R^{γ}_{pA} are needed.

Direct photon production at the LHC in p+A collisions

Rezaeian, arXiv:1210.2385



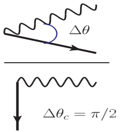


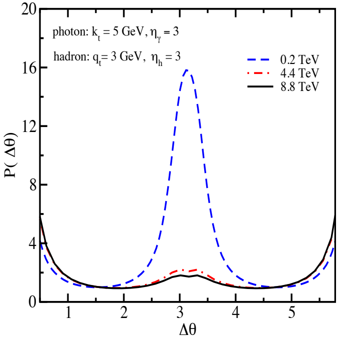
Prompt photons are not suppressed in QGP, but are subject to suppression in CGC medium due to gluon saturation.

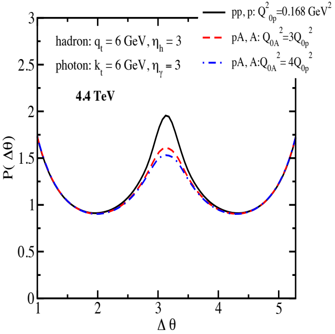
See also Thomas Peitzmann`s talk

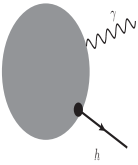
Photon-hadron correlations in high-energy pA collisions: $p + A \to \gamma + h + X$

$$P(\Delta\theta) = \frac{d\sigma^{p(d)\,T \to h(q)\,\gamma(k)\,X}}{d^2\vec{b}_t\, dk_t^2\, dq_t^2\, dy_\gamma\, dy_l\, d\theta}[\Delta\theta] \Big/ \frac{d\sigma^{p(d)\,T \to h(q)\,\gamma(k)\,X}}{d^2\vec{b}_t\, dk_t^2\, dq_t^2\, dy_\gamma\, dy_l\, d\theta}[\Delta\theta = \Delta\theta_c] =$$

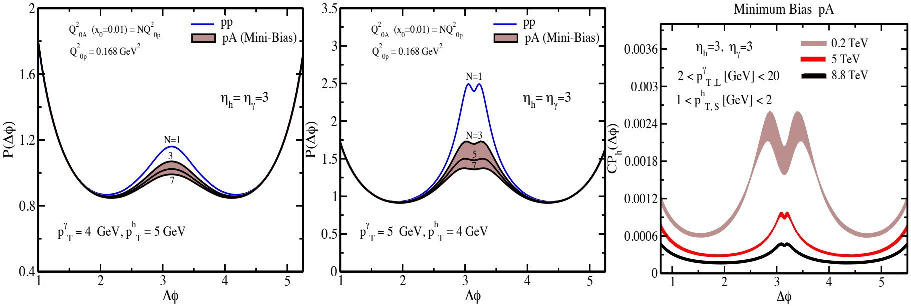








- Existence of the saturation scale unbalances the back-to-back correlations.
- Denser nuclei **or/and** Higher energy **or/and** Lower transverse momenta (larger saturation scale) → more suppression of away-side correlations.



Rezaeian,PRD86, arXiv:1209.0478; PLB718, arXiv:1210.2385

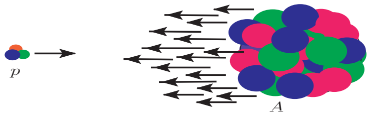
Photon-hadron correlations have a double peak structure if:

$$z_T = \frac{p_T^h}{p_T^\gamma} \leq 1 \quad \text{and} \quad p_T^\gamma \frac{(e^{\eta_h} + e^{\eta_\gamma})}{\sqrt{S}} \leq 1.$$

Emergence of double peak structure is an excellent probe of saturation dynamics.

- **Challenge**: Standard (DGLAP-like) QCD calculations cannot reproduce none of $\gamma - \pi^0$ correlation features.

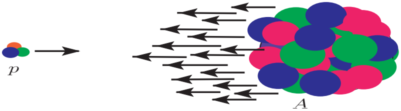
If there would be flow in pPb collisions→ more difficult to pin down the true nature of the initial glass



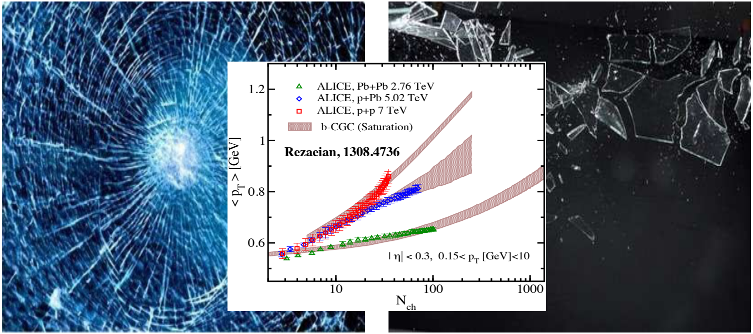
Color–Glass–Condensate in pPb

Collective flow in pPb collisions

Which one we have seen at the LHC??



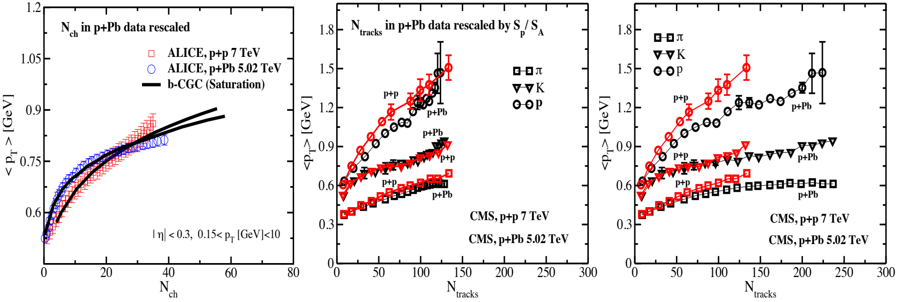
Color–Glass–Condensate in pPb **Collective flow in pPb collisions**



- $\langle p_T \rangle$ and its correlation with N_{ch} $\rightarrow$ to discriminate underlying particle production mechanism.
- If the flatness persists at higher N_{ch} $\rightarrow$ the importance of final-state effects like hydrodynamic.

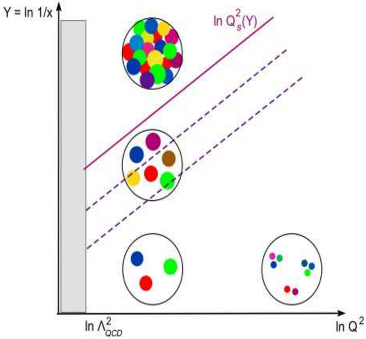
Geometric scaling in p+Pb at the LHC

Plots from: Rezaeian, arXiv:1308.4736



- Can final-state type approaches like hydrodynamic explain this scaling phenomenon?
  See also: McLerran, Praszalowicz, Schenke, arXiv:1306.2350.
  For discussion on $S_{p,A}$: Bzdak, Schenke, Tribedy and Venugopalan, arXiv:1304.3403.
  For discussion on Q_s dependence: Dumitru and McLerran, hep-ph/0105268.

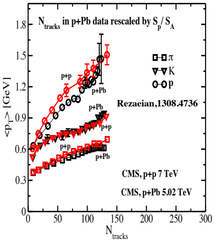
Physics is invariant along any line parallel to the saturation line



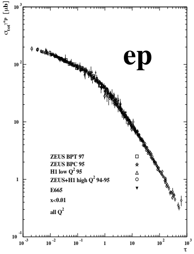
- **The observables scale as functions of the ratio** $Q^2/Q_s^2(Y)$: only depend on the difference $\ln Q^2 - \ln Q_s^2(Y) = \ln(Q^2/Q_s^2(Y))$
- The small-x evolution eq. (BK-JIMWLK eq.) has geometric scaling property.

Evidence of saturation: Geometric scaling in e+p, e+A, p+p, p+A

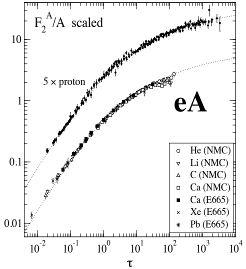
McLerran, Praszalowicz, Schenke (2013), Rezaeian (2013)



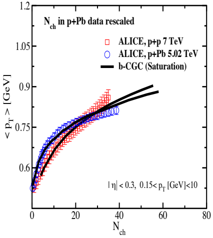
Stasto, Golec–Biernat, Kwiecinski (2000)



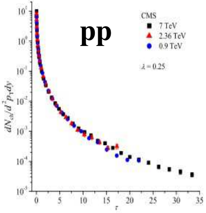
Freund, Rummukainen, Weigert, Schaefer (2002)



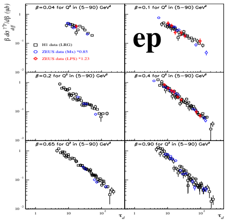
Rezaeian (2013)



McLerran, Praszalowicz (2010)



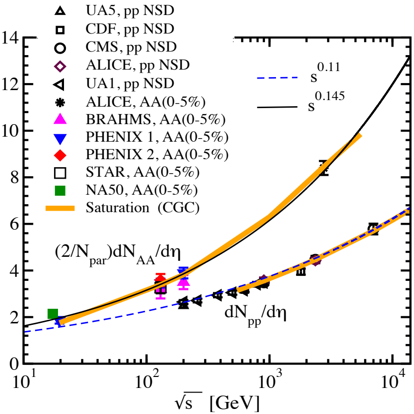
Marquet, Schoeffel (2006)



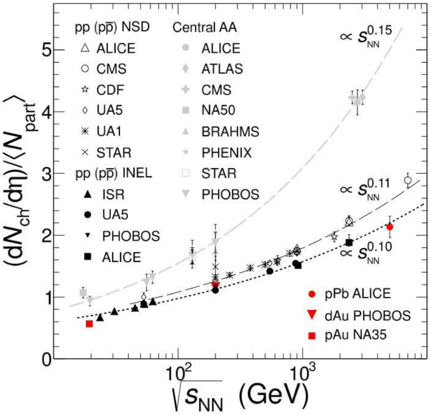
The geometric scaling observed in different reactions can be naturally(and only) explained in the CGC approach→ universality at small-x.

Universality of particle production at small-x at different energy: p+p, p+A, A+A

Levin, Rezaeian, arXiv:1102.2385



ALICE collaboration, arXiv:1210.3615

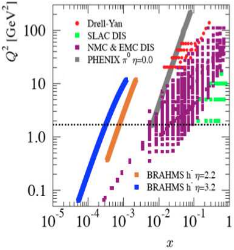


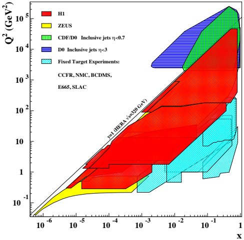
$$\frac{dN_h}{d\eta} \quad \propto \quad Q_s^2 \propto s^{\lambda/2} = s^{0.10\div0.145}$$

Conclusion:

Await to be verified at the LHC in p+Pb run:

- Slow rise of $\langle p_T^h \rangle$ with N_{ch}.
- Suppression of inclusive charged hadron at *very* forward rapidities.
- Suppression of inclusive (and direct) photon production at *very* forward rapidities.
- Suppression of away-side photon-hadron (and dihadron) correlations at forward rapidities.
- Appearance of double peak structure for away-side $\gamma - \pi^0$ correlations at forward rapidities.





- Available data (HERA+RHIC+LHC) cannot **uniquely** determine the initial condition (initial saturation scale) of the BK equation.

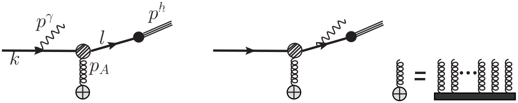
  For proton: $p_t \leq 6$ GeV, $x \leq 0.01$: $Q^2_{0p} \approx 0.168\,\mathrm{GeV}^2$ with $\gamma \approx 1.119$

- For heavy nuclei: $Q^2_{0A} = \mathbf{c} A^{1/3}\; Q^2_{0p}$,

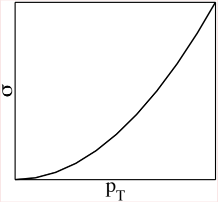
  $p_t \leq 4$ GeV, $x \leq 0.01$: $\mathbf{c} \approx 0.5 \Longrightarrow Q^2_{0A} \approx (3 \div 4) Q^2_{0p}$

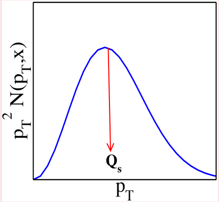
$$R^{ch}_{pA}(p_T >> 1) = \frac{Q^2_{0A} S_A}{Q^2_{0p} A S_p} \approx \frac{Q^2_{0A}}{Q^2_{0p} A^{1/3}} \to 1 \Longrightarrow Q^2_{0A} = \mathbf{c} A^{1/3}\; Q^2_{0p} \text{ with } \mathbf{c} \approx 1$$

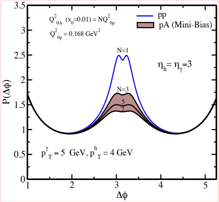
$\mathbf{c} \approx 0.5 \div 1 \Longrightarrow Q^2_{0A} = N Q^2_{0p}$ with $N = 3 \div 7.$



Photon-hadron correlations have a double peak structure because:



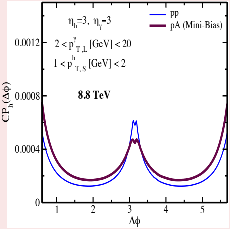


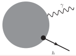


1. If the projectile parton does not exchange transverse momentum with target, the production rate of photon-hadron goes to zero. $p_T = |\vec{l_T} + \vec{p_T}^{\gamma}| = 0 \to \sigma^{h\gamma}(q + A \to \gamma(p^\gamma) + q(l) + X)$=0
2. Existence of saturation scale: $p_T^2 N_F(p_T, x_g)$ in $\sigma^{h\gamma}$ has a maximum at $p_T \sim Q_s$.
3. Because of convolution with fragmentation and parton distribution functions→ local minimum will not be zero but gets smeared out.

$\pi^0 - \gamma$ coincidence probability in pA@LHC

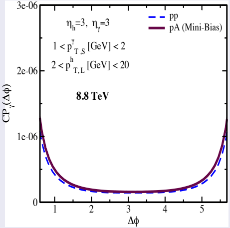
Trigger(leading) particle is a prompt photon ($p_T^h < p_T^\gamma$) :

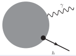




$$CP_h(\Delta\phi; p^h_{T,S}, p^\gamma_{T,L}; \eta_\gamma, \eta_h) = N_h^{\text{pair}}(\Delta\phi)/N_{\text{photon}}$$

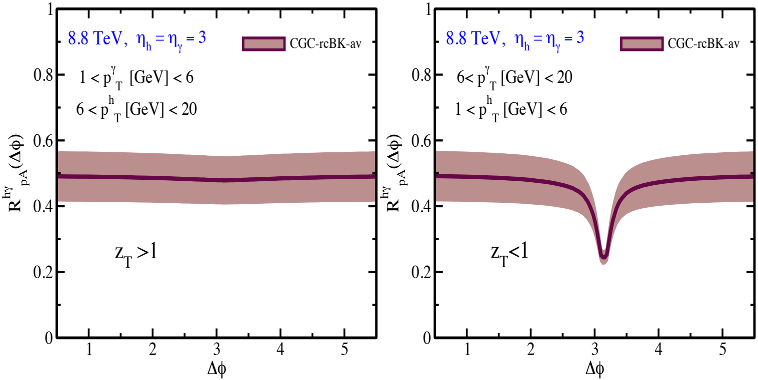
Trigger particle is a hadron ($p_T^h > p_T^\gamma$):





$$CP_\gamma(\Delta\phi; p^\gamma_{T,S}, p^h_{T,L}; \eta_\gamma, \eta_h) = N_\gamma^{\text{pair}}(\Delta\phi)/N_{\text{hadron}}$$

Nuclear modification of semi-inclusive $\gamma - \pi^0$ production



$p^h_T > p^\gamma_T$ $\qquad$ $p^h_T < p^\gamma_T$